Fe Kα line: A tool to probe massive binary black holes in Active Galactic Nuclei?

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ABSTRACT

Hierarchical mergers of galaxies can form binary black holes (BBHs) since many or most galaxies have central massive black holes (BHs). It is possible that some BBHs exist in active galactic nuclei (AGNs). We argue that each BH may be surrounded by an accretion disc with a different inclination angle to the line of sight (due to different BH spin directions and the Bardeen-Petterson effect). The observed Fe Kα line profile from a BBH system is a combination of the lines from the inner regions of the two discs, which is significantly affected by the inclination angles of the two discs. The Fe Kα line profile associated with BBHs may have an unusual shape with double or more peaks as well as short-term variability, which can be distinguished from the Fe Kα line properties of some other possible models. We suggest that with the improvement of resolution in X-ray astronomy, Fe Kα line profiles be a potential tool to probe the existence of massive BBHs in AGNs. The Fe Kα line profile associated with BBHs may also provide a tool to investigate the dynamics in strong gravitation field (e.g. providing evidence of the Bardeen-Petterson effect).

Subject headings: Black hole physics–Accretion–Line profile–galaxies: active

1.   Introduction

Much evidence indicates that massive black holes (BHs) reside in the centers of many or most galaxies (e.g. Magorrian et al. 1998). Mergers of galaxies are likely to form massive binary black holes (BBHs). Theoretical estimation shows that the BBH lifetime is not much shorter than the Hubble time and many BBHs should be still in the centers of galaxies (Begelman, Blandford & Rees 1980). The existence of BBHs in the universe will not only provide a laboratory to test gravitation

radiation theory and BH physics, but also probe of the hierarchical structure model of galaxy and large-scale structure formation.

Currently, there is no systematic and unambiguous method to identify BBHs. BBHs stay at a separation in the range $10^{16} - 10^{19}$cm (e.g. $10^{-4} - 10^{-1}$ arcsec at 10Mpc) during the slowest evolution period (Begelman, Blandford & Rees 1980, Yu 2002), and thus it is hard to resolve a BBH — two very close galactic nuclei in the image — with current telescope resolution. The shallow cusps in the inner surface brightness profiles of some nearby giant galaxies may be produced from steep cusps by ejecting stars from their inner regions during the hardening of BBHs (Faber et al. 1997, Quinlan & Hernquist 1997), but there is still no proof of a currently existing BBH in those galaxies. To identify a BBH, we have to find some other effect of BBHs on their nearby environment and/or some manifestation of the motion in a two-body system, such as jet precession (Begelman, Blandford & Rees 1980), double-peaked Balmer lines (Gaskell 1996), or quasi-periodic radio, optical, X-ray or γ-ray variation (e.g. OJ287: Sillanpää et al. 1988, Valtaoja et al. 2000; Mkn501: Rieger & Mannheim 2000). Some active galactic nuclei (AGNs) have been claimed to be detected as BBH candidates by those methods, but all of them are controversial because of other explanations for the same phenomena or some inconsistency with other observational evidence.

If there is sufficient gas with some angular momentum close to a BBH, we may expect that the gas in the vicinity of each BH is accreting onto the BH in the form of a disc rather than in the form of spherical accretion, which may make the system appear as an AGN. If the binary separation is small (say, much less than the scale of the broad line region), the two accretion discs may be warped at outer parts and connected with an outer large circumbinary accretion disc. If the separation is large enough, each BH is probably accompanied by its own disc and broad line region. The spin axes of the two BHs are very likely to be misaligned (Rees 1978, Begelman, Blandford & Rees 1980) and the discs in this two-accretion-disc (TAD) system associated with the BBH can also have different inclination angles to the line of sight.

AGNs are observed to be copious X-ray emitters. This X-ray emission is believed to originate from the very inner accretion disc around a massive BH. The broad skewed iron Kα line profile found by *GINGA* and confirmed by *ASCA* is believed to result from a combination of gravitational broadening and Doppler shift in an accretion disc (Tanaka et al. 1995). So far, alternative models have failed to account for this profile (Fabian et al. 1995, Fabian et al. 2000), which offers one of the strongest lines of evidence for the existence of massive BHs. X-ray spectroscopy also promises a powerful tool to detect strong-gravitation-field relativistic effects in the vicinity of a massive BH. The observed Fe Kα line profile is significantly affected by the inclination angle of the disc to the observers line of sight (Fabian et al. 1989, Laor 1991). In a BBH system, the observed Fe Kα line profile can be a combination of the line profiles from two discs with very different inclination angles to the line of sight. Motivated by this observation, we propose a method to probe BBHs in AGNs by Fe Kα line profiles. We expect that Fe Kα line profiles will become an efficient way to probe BBHs in AGNs.

2. Two accretion discs in BBH systems

Consider a BBH containing BHs of mass m_1 and m_2 rotating around their center of mass (Fig. 1), the relative orbit of the two BHs is assumed to be circular with separation a. The Keplerian orbital period of the binary is

$$P^{\mathrm{orb}} = 210 \left(\frac{a}{0.1\mathrm{pc}}\right)^{3/2} \left(\frac{2 \times 10^8 M_\odot}{m_1 + m_2}\right)^{1/2} \mathrm{yr} \tag{1}$$

and their maximum orbital velocities relative to the center of mass in the line of sight are

$$|v_i| = 1.5 \times 10^3 \mathrm{km/s} \left(\frac{0.1\mathrm{pc}}{a}\right)^{1/2} \left(\frac{m_1 + m_2}{2 \times 10^8 M_\odot}\right)^{1/2} \left[\frac{2m_1 m_2}{m_i(m_1 + m_2)}\right] \sin\theta_{\mathrm{orb}} \quad (i = 1, 2) \tag{2}$$

where θ_{orb} is the orbital inclination to the line of sight. A moderate orbital eccentricity of the BBH orbit will not change the above values much. The orbital motion of each BH is ignored in the later calculation of Fe Kα line profiles since it only causes a slight overall Doppler shift in the profiles.

For a single rapidly rotating BH with mass m, the Bardeen-Petterson effect (Bardeen & Petterson 1975) can cause the gradual transition of the disc into the BH equatorial plane in the region between radii $10^4 r_{\mathrm{g}}$ and $10^2 r_{\mathrm{g}}$ (note that there are still controversies on the location of the transition radii, c.f. Nelson & Papaloizou 2000 and references therein), where $r_{\mathrm{g}} = Gm/c^2$. Thus a planar disc could be formed in the equatorial plane of the BH. The timescale for the BH to align with the outer disc angular momentum cannot be estimated precisely, but is of the order of the overall lifetime of AGNs (Rees 1978, Nelson & Papaloizou 2000; however, a much smaller realignment timescale of the order of 10^5 yr is gotten by Natarajan & Pringle 1998). In a BBH system, it is likely that both BHs have large spins and the spin axes can be in very different directions, especially in the early phase of the nuclear activity. This difference may not be changed in a time much shorter than the lifetime of the nuclear activity. Therefore, the two accretion discs associated with a BBH can have different inclination angles to the line of sight. Even if only one of the BHs has a large spin, it is still very likely that its spin axis is different from the disc direction of the other (Schwarzschild) BH.

The Roche radius of the smaller BH is about $(m_2/3m_1)^{1/3}a$ if $m_1 > m_2$. If the two BHs have comparable masses and a typical separation of $\sim 10^4 G(m_1 + m_2)/c^2$, the inner region of each disc, at least within $r \lesssim 10^3 Gm_i/c^2$, is not easily disrupted by tidal forces from the other BH. In a BBH system, the spin axis of each BH will undergo geodesic precession about its total angular momentum as discussed by Begelman, Blandford & Rees (1980). When the spin angular momentum of the binary is small compared with its orbital angular momentum ($m_2/m_1 \gtrsim \sqrt{Gm_1/ac^2}$ if $m_1 > m_2$), the spins will precess in a cone with the orbital angular momentum as axis. Their precession periods are given by:

$$P_i^{\mathrm{prec}} \sim 6 \times 10^6 \left(\frac{a}{0.1\mathrm{pc}}\right)^{5/2} \left(\frac{m_1 + m_2}{2 \times 10^8 M_\odot}\right)^{1/2} \left(\frac{10^8 M_\odot m_i}{m_1 m_2}\right)^2 \mathrm{yr} \quad (i = 1, 2). \tag{3}$$
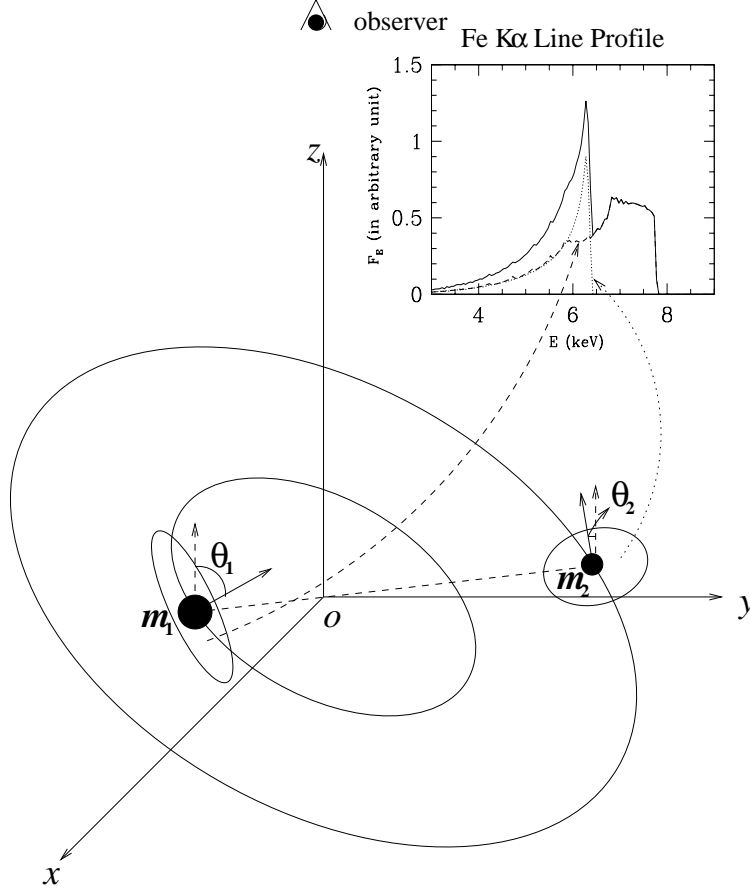
Fig. 1.— Schematic diagram of a BBH and its accretion discs: the BBH containing BHs m_1 and m_2 is rotating around the center of mass 'O' in circular orbits. A distant observer is located in the z-axis direction. The inclination angles of the two discs to the line of sight are θ_1 and θ_2, respectively. An example of Fe Kα line profile is plotted in the upper-right of this figure by setting $\theta_1 = 60°$, $\theta_2 = 5°$, the emissivity ratio $\epsilon_2^0/\epsilon_1^0 = 0.6$ (or equivalently the mass ratio $m_2/m_1 = 0.6$ by assuming the two discs have almost the same dimensionless accretion rates), and $p = 2.5$ (the exponent of the emissivity law in §3). The dashed line represents the component from the disc of the BH m_1 and the dotted line represents the component from the disc of the BH m_2. The solid line is the observed line profile, which is a combination of the two components.

The precession may cause the two accretion discs to be tilted to their BHs equatorial plane, but the two disc inclination angles to our line of sight will not change in a short time. Detailed study of the dynamics and stability of the TADs in BBHs is beyond the scope of this paper.

3.   Emergent Fe Kα line profiles from BBH systems

We have argued that there are good reasons for the existence of TADs with different inclination angles to the line of sight in BBHs. We shall assume that both discs are cold thin accretion discs. The observed Fe Kα line profile is then the summation of the two components from the TADs. The combined line profile is mainly controlled by the inclination angles of the TADs and the relative strength of the two components. The relative strength is related to the mass ratio of the two BHs and the accretion rates onto them (if the two accretion systems have almost the same dimensionless accretion rate $\dot{m} = \dot{M}/\dot{M}_{\mathrm{Edd}}$, where $\dot{M}$ is the accretion rate and $\dot{M}_{\mathrm{Edd}}$ is Eddington accretion rate, the relative strength of the two components will be given by the mass ratio m_1/m_2).

Using the ray-tracing technique and elliptic integrals (Rauch & Blandford 1994), we follow the photons from each accretion disc to a distant observer, and calculate the corresponding redshift of the photons and the resulting line profiles. The spins of BHs are both set to be $a/M = 0.998$. The Fe Kα line photons are assumed to be isotropically emitted in the frame moving with the accretion disc material, and the surface emissivity is given by the power-law $\epsilon_i(r) = \epsilon_i^0 r^{-p}$ for the region $r_i^{\mathrm{in}} \leq r \leq r_i^{\mathrm{out}}$. We adopt the averaged line emissivity exponent index of $p = 2.5$ which is obtained from the fitting of Fe Kα line profiles for a sample of AGNs observed by $ASCA$ (Nandra et al. 1997). We set the inner radius to be the marginally stable orbit r_{ms} (few Fe Kα line photons come from the region inside the marginally stable orbit for Kerr BH with spin 0.998), and the outer radius $r_i^{\mathrm{out}} = 160 G m_i/c^2$ (the line profiles are not sensitive to the value of r_i^{out} since most line photons come from the inner region for a typical line emissivity law with $p = 2.5$). An example of the resulting spectral line is shown in Figure 1, for discs with inclination angles $\theta_1 = 60^{\mathrm{o}}$ and $\theta_2 = 5^{\mathrm{o}}$, and $\epsilon_2^0/\epsilon_1^0 \sim m_2/m_1 \sim 0.6$. This unusual line profile is double-peaked, asymmetric and has two 'edge'-like feature. The peak with the smaller central energy, near the rest frame energy of Fe Kα line – 6.4keV, (or less than 6.4keV due to gravitational redshift for extremely low inclination disc), comes from disc D_2 with a small inclination angle, has the characteristic features of emission from a relativistic accretion disc: a skewed red wing and a sharp "blue" edge (note that the energy of the "blue" edge is mainly determined by the inclination of a disc, and the red wing extent is sensitive to the inner radius of the line emission region). The peak with the smaller central energy is narrower than the broad component, which comes from disc D_1 with a high inclination angle. If the spin of the BH m_1 is smaller, the "narrow component" can be even narrower. The "narrow" component can be stronger or weaker than the broad component depending on the relative emissivity. Another important feature is that these two components should both have *short-term variability* of intensity and shapes on the timescale of 10^4s, as suggested by the variation in some Seyfert galaxies (Iwasawa et al. 1996, Nandra et al. 1999), and their variation patterns can be totally different and unrelated

with each other since they come from two different discs. All of the above features make it easy to distinguish the BBH model from the other alternative models producing a two-component line shape.

Not all of the emergent Fe Kα line profiles from TAD systems are so distinguishable from the profiles produced by only one disc. If the relative emissivity of the two discs is too small or too large, the component emitted from one accretion disc in TADs system will be drowned by the other. Only when $\epsilon_2^0/\epsilon_1^0$ is about in the range $0.2 - 2$ (or m_2/m_1 is in a similar range if luminosity is proportional to Eddington luminosity) will the line profiles from TADs be significantly different from the one emitted by a single BH–accretion disc system. If $\epsilon_2^0/\epsilon_1^0$ is a little less than 0.2, the line profile may be misunderstood as a relativistic line from a single disc plus an absorption feature; and if $\epsilon_2^0/\epsilon_1^0$ is a little larger than 2, the line profile may be misunderstood as a relativistic line from a single disc plus a high ionization line (e.g. Fe Kβ or Ni Kα line). If the difference between θ_1 and θ_2 is too small, the two line components will be blended, and thus difficult to distinguish from the profile produced by a single BH–accretion disc system. The line profiles in TAD systems can be very complicated with double peaks, three peaks and even four peaks depending on the inclination angles of the two accretion discs and the relative emissivity (Fig. 2). When $\theta_1 \sim 45^{\rm o} - 70^{\rm o}$ and $\theta_2 \sim 0^{\rm o} - 20^{\rm o}$, the emergent line profile will clearly exhibit two distinct components (see Fig. 2; note that the line from a disc with very high inclination angle (say, $> 70^{\rm o}$) may be strongly affected by the limb-darkening effect of the outer layer of accretion disc). If the inner disc is somewhat ionized, or the emissivity law is somewhat different, the line profile should remain similar. The probability that the combined line from two randomly oriented equal discs is in the shape similar to those shown in Figure 2, is about 20% (the difference between the inclination angles is larger than $30^{\rm o}$ and both the disc inclination angles are not larger than $70^{\rm o}$). The amounts of AGN sources expected to harbor BBH systems with comparable BH masses, which could be identified by Fe Kα line profiles, are relevant to the process of structure formation and the merger history of galaxies.

The line shapes from the TAD systems shown in Figure 1 and Figure 2 are examples chosen from many idealizations. We have neglected such complication as the actual dynamics of the system, the possible warp of the outer disc, the ionization of the accretion discs, the real line emissivity law, contamination from non-disc emitters, the irradiation of one disc by the X-ray photons from the other, and the absorption of intervening gas and dust etc. The complication certainly affects the line profile quantitatively, but will not make much difference qualitatively.

4. Differentiating the BBH model from other possible models

There are other possible models that can produce two-component line profiles, but they are not difficult to differentiate from the BBH model.

First, off-axis X-ray flares above a single disc can strongly affect the line profiles (off-axis-flare model; c.f. Yu & Lu 2000). In §3, the disc emissivity is assumed to be axisymmetric. In reality,
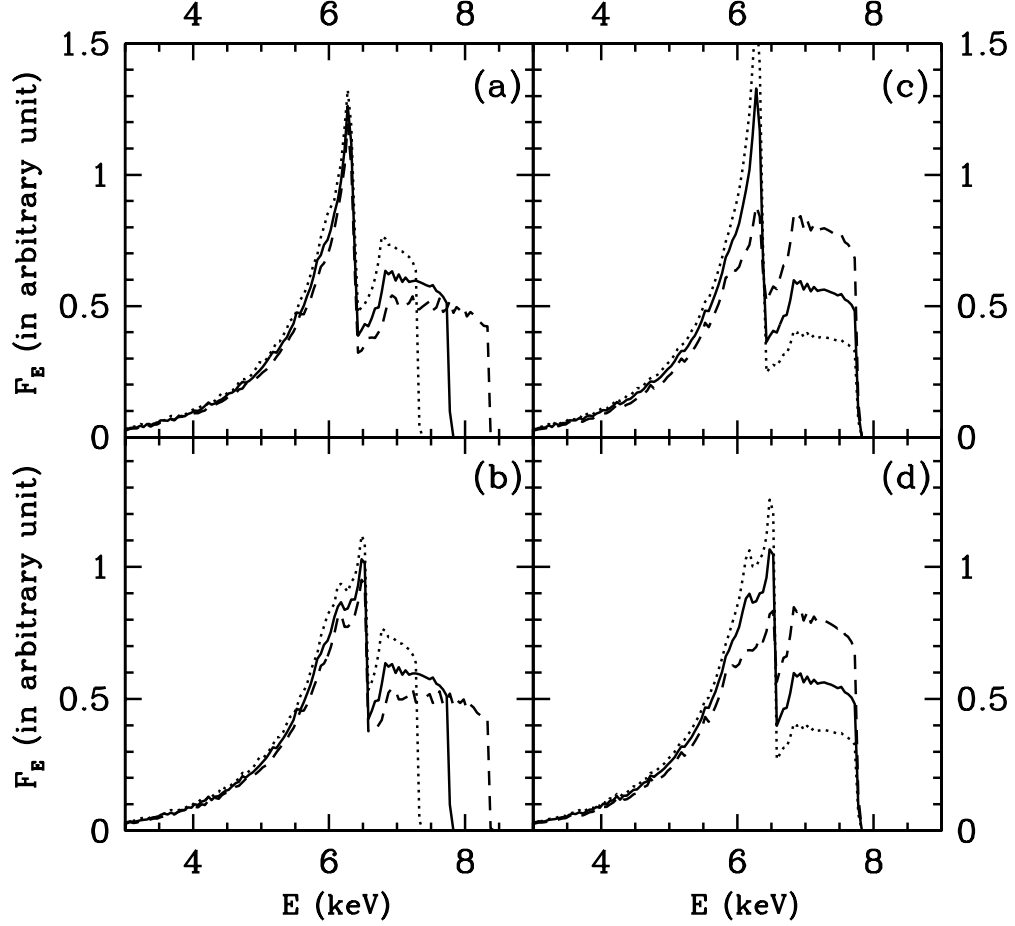
Fig. 2.— Fe Kα line combined profiles from TADs in BBHs. The exponent index of the emissivity law p is 2.5. In panels (a) and (b) $\epsilon_2^0/\epsilon_1^0 = 0.6$, $\theta_1 = 50^{\circ}$ (dotted line), 60° (solid line), 70° (dashed line), but $\theta_2 = 5^{\circ}$ in (a) and $\theta_2 = 20^{\circ}$ in (b). In panels (c) and (d) $\epsilon_2^0/\epsilon_1^0 = 1.5$ (dotted line), 0.7 (solid line), 0.2 (dashed line), $\theta_1 = 60^{\circ}$, but $\theta_2 = 5^{\circ}$ in (c) and $\theta_2 = 20^{\circ}$ in (d).

X-ray flares can be off the disc rotation axis and the emissivity law of the disc is non-axisymmetric because the disc region just under the flares generally receive more illumination. Thus, the non-axisymmetric emissivity may strongly affect the Fe Kα line profiles since different energy parts of Fe Kα line profiles stem from different regions of a disc. For example, a cold accretion disc is illuminated by two local flares: one is atop the approaching side of the disc, where the energy of Fe Kα line photons are blue shifted by Doppler effect; and the other is atop the disc region towards or backwards us which corresponds to the line emission around 6.4keV. This situation can make line shapes like the one from TADs. The X-ray flares are probably produced by some thermal instability in the disc or magnetic reconnection and their locations should be randomly distributed. The appearance of the line profile arising from flares can be very complex. However, the average line profile over several flares should be consistent with the profile from a single disc (with a single inclination angle), as suggested by the observations of MCG-6-30-15 (Iwasawa et al. 1996, Iwasawa et al. 1999), which is quite different from the combined line profiles from TADs.

Second, a two-component line shape can be produced if a narrow line component is emitted from a molecular torus or broad line region (BLR) clouds, and a broadened line component is emitted from the inner region of a highly inclined accretion disc (BLR/Torus-AD model, c.f. Yaqoob et al. 2001). In this scenario, the central energy of the narrow component should be around 6.4keV or a little blue-shifted by the outflow motion, and the line width caused by the velocity dispersion of the clouds should be several thousand km/s.[1] In contrast, in the BBH model, the "narrow" component is redshifted to energies less than 6.4keV if the inclination is very low (due to gravitational redshift). With higher inclination, the narrow component is centered around 6.4keV or higher, but with a large width. More importantly, in the BLR/Torus-AD model, the narrow component should remain constant on the timescale of several days or more (the light-travel time across the BLR or the torus) rather than varying on timescales $< 10^4$s, as predicted by the BBH model.

Third, a two-component line shape can also be produced by the combination of a broadened iron line from a highly inclined accretion disc plus a component which is scattered into our line of sight by an efficient electron-scattering material (Scatter-AD model, c.f. Wang et al. 1999). It is unlikely that this electron-scattering material is close to the disc because this configuration is unlikely to produce a line with two distinct components: first, the scattered line component shape will be different from the one observed from a disk with a small inclination angle; second, Fe Kα photons from the inner accretion disc cannot be seen directly because the disc is covered by the scattering material. If the scattering layer is high enough above the disc, the scattered line profile would be somewhat like the one observed at a small inclination angle; however, the covering factor would normally be small and the equivalent width of this component should therefore be

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[1]In AGNs, the blueshift of high ionization lines (e.g. CIV line) suggests that the outflow of the line emission gas in BLR has a velocity from zero to several thousand km/sand no evidence about the inflow motion of emission materials in BLR has been found (Sulentic et al. 2000).

much smaller than the broad one since the scattered photons are redistributed in all directions. In contrast, in the BBH model, the equivalent width of the "narrow" component can be larger than that of the broad component. Furthermore, the temporal variations of the two components in the Scatter-AD model must be strongly correlated with a time delay which reflects the distance between the scattering material and the disc.

5. Prospects

To use Fe Kα profiles to identify a BBH with TADs, we need to resolve both the narrow component and broad component of the line profiles and study the variation of the line profiles and intensity with time. Over the past decade, a number of Seyfert galaxies and QSOs have been shown to have broad Fe Kα lines (Nandra et al. 1997, Yaqoob & Serlemitsos 2000). The Fe Kα line profile of NGC4151 is fitted by two disc components with inclinations of 0° and 58° better than by a one-disc line model (Wang et al. 1999). The component with inclination 0° was explained by being scattered into our line of sight; however, those two components can also be explained as coming from possible TADs. Future observations with higher resolution are needed to check if NGC4151 is a possible BBH candidate. The unique Fe Kα profile of MARK205 (see Fig. 2 in Reeves et al. 2000), recently revealed by *XMM-Newton*, is somewhat like the line shape established in Figure 1. Its broad line component can be fitted by an accretion-disc line with a high inclination. Unfortunately, the narrow component is not fully resolved. The present observations can be explained by assuming that the narrow component comes from neutral matter at large distant from a central BH and the broad one is emitted from a highly ionized relativistic accretion disc (Reeves et al. 2000). So, further observations and variability studies are needed to check if this object is a BBH candidate or not.

Stimulated by those special line shapes observed in some objects, we believe that some BBHs in AGNs, if any, can be identified by searching the unusual iron line profile with current and future X-ray satellites, such as *XMM-Newton, Constellation-X and XEUS*. If any one of AGNs is revealed to have the typical line shapes shown in Figure 2 as well as short-term variability, it will provide one of the strongest lines of evidence for the existence of BBHs and a laboratory to investigate the dynamics in strong gravitation field (e.g. the Bardeen-Petterson effect).

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